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Development of a Low-swirl Injector for Midsize Gas Turbines and Fuel Flexible Combustors

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Project Overview

- **Goals/Objectives**
  - Adapt a nascent low-swirl combustion method to ultra-low emission fuel flexible MW size gas turbines
- **Timelines**
  - Feasibility studies (FY99-01)
  - Proof-of-concept prototype demonstration (FY 02-03)
  - Prototype development and demonstration for natural gas engines (FY 04-05)
  - Further development for fuel-flexibility (FY 06-08)
- **Budgets** FY04 - $500K, FY05 - $350K
- **Team/Partnerships**
  - **LBNL** – science and technology foundation
  - **Solar Turbines** – engineering design and implementation

Motivation & Needs

- Technologies for ultra-low emissions gas turbines impacts system integration, compatibility, operation, durability, maintenance and cost
  - Catalytic combustors, surfaced stabilized injector , and active control methods are effective but questions remain on their engine readiness
- Circumvent these obstacles by developing an ultra-low emission combustion method that is readily adaptable to current engines
  - Exploit simple yet sophisticated low-swirl combustion for gas turbines

Low-swirl Combustion

- Low-swirl combustion (LSC) is a flame stabilization mechanism discovered at LBNL
    - Spin-off technology from DOE basic research
    - Requires new theoretical explanation
- – Technology transfer
    - 2 US patents
    - Basic knowledge applied to develop practical implementations and scaling and engineering rules
    - Maxon Corp. Commercialized LSC for direct industrial process heaters (two lines of products)
        - – Meeting most stringent air-quality rules in US

LSC Has a Signature Lifted Flame

Burner made of PVC to showcase the uniqueness of the LSC concept

- Low-swirl combustion exploit the "propagating wave" property of premixed flames
  - Patented swirler optimized to generate a divergent flow where the flame can freely propagate
  - Flame position not highly sensitive to inflow velocity and mixture stoichiometry
  - Supports stable flame at ultra-lean ultra-low emissions conditions

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Patented swirler for LSC

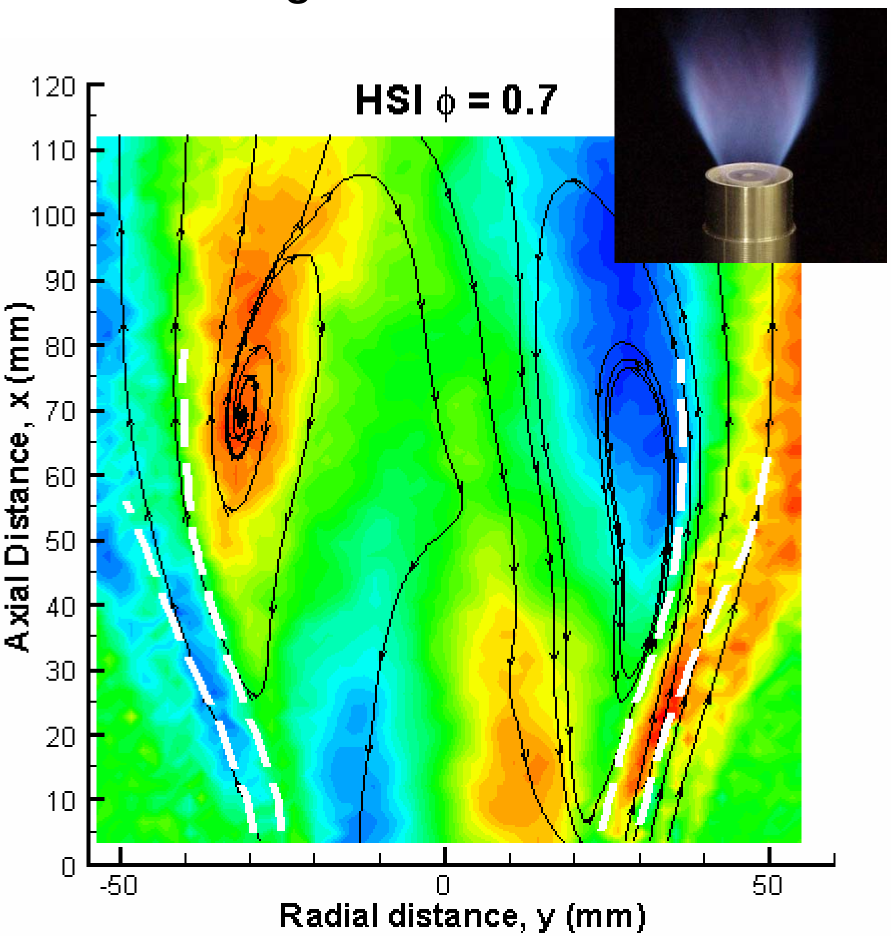
- Engineered to inhibit the formation of flow recirculation
- Derived a new definition of swirl number, S, to characterize swirl rate and for scaling

$$S = \frac{2}{3}\tan\alpha \frac{1-R^3}{1-R^2+[m^2(1/R^2-1)^2]R^2}$$

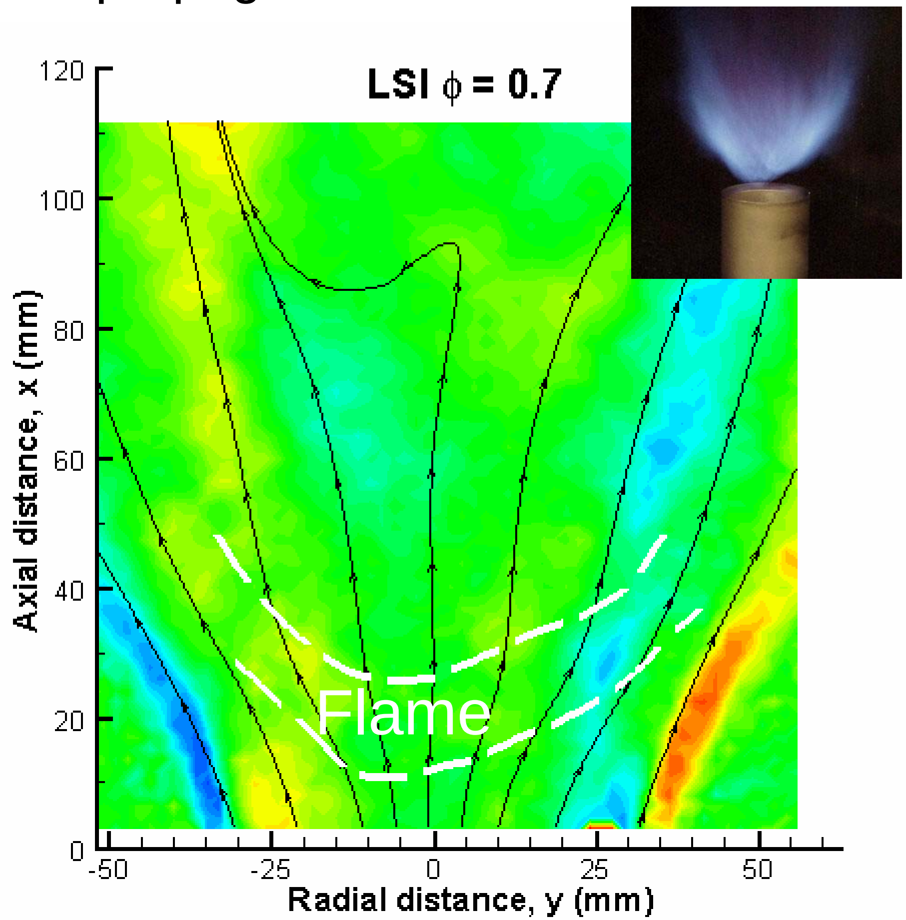
- **Center channel to injector radii ratio , $R = R_c/R_b$**
- **Vane angle, α**
- **Flow split between center channel and swirl annulus, m**

LSC is flame stabilization without recirculation

- Conventional high-swirl injector generates backflow for flame anchoring



- Low-swirl injector generates flow divergence where the flame freely propagates



Adapting LSC to Gas Turbine

- Accomplishments FY99-03
  - FY99: verified LSC concept at turbine conditions using a low-swirl burner with air jets
  - FY00: demonstrated 3" industrial LSB at gas turbine conditions
  - FY01: established research & development plans for swirler design, premixer and staging
  - FY02: designed proof-of concept low-swirl injector (LSI) based on SoLoNOx swirler
  - FY03: demonstrated < 2 ppm NO_x at gas turbine conditions

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FY04-05 Objectives

- Development of a fully functional LSI prototype
  – Confirm LSI operability within a typical engine cycle

- Demonstrate engine readiness
  – Configure the LSI to be “Plug-in” injector replacement for SoLoNOx Taurus 70 (T70)

Barriers and Strategy

- Key technical barriers
  - Integration of a pilot and premixer to LSI
    - Interferences on LSC mechanism & emissions
  - Operability (light-off, on load & off load protocol, response to off-design conditions)
  - Injector to injector interactions
  - Combustion oscillations
- Strategy
  - A scientific approach guided by basic understanding of LSC principle and supported by laboratory studies and rig tests
  - Leveraging knowledge and insights from prior DLN developments

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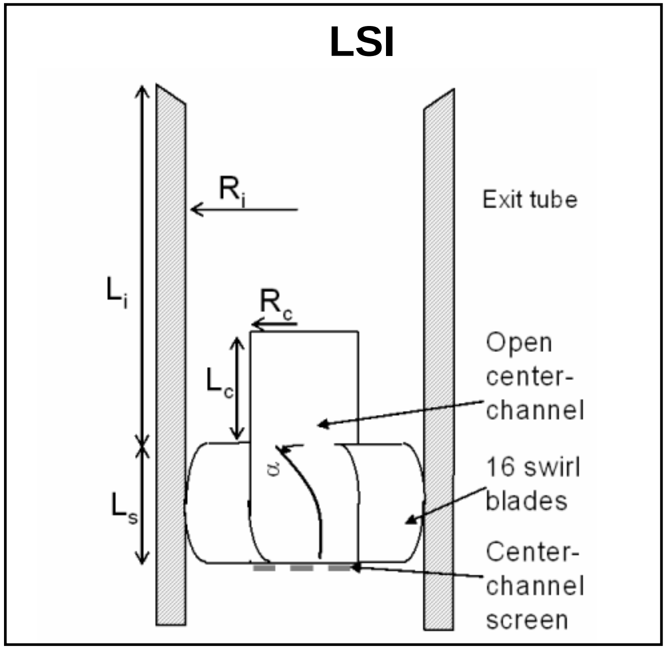
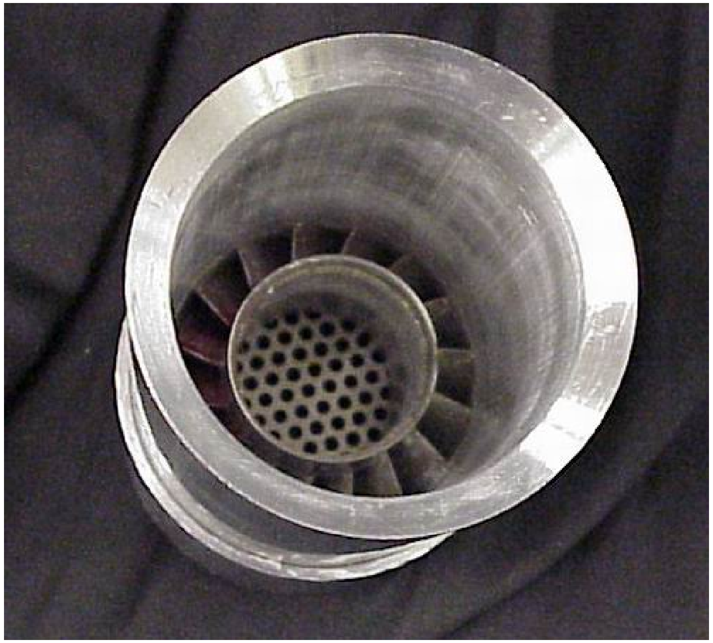
FY04-05 Milestones

- Developed fully functional LSI prototype
  - Optimized pilot placement and premixer design through laboratory experiments and rig tests
  - Designed, fabricated and tested an engine compatible LSI prototype
  - Single injector rig-tests verified stable operation within a wide window with NO_x < 3 ppm
- Tested a set of engine-ready LSIs in annular combustor liner
  - Met operability and ultra-low emission metrics
- Skipped costly developmental partial pressure rig tests and proceeding to T70 tests
  - Significant reduction in development cost
- Developed an empirical model for adaptation to fuel flexible turbines

LSI-1 Prototype from FY03 Works

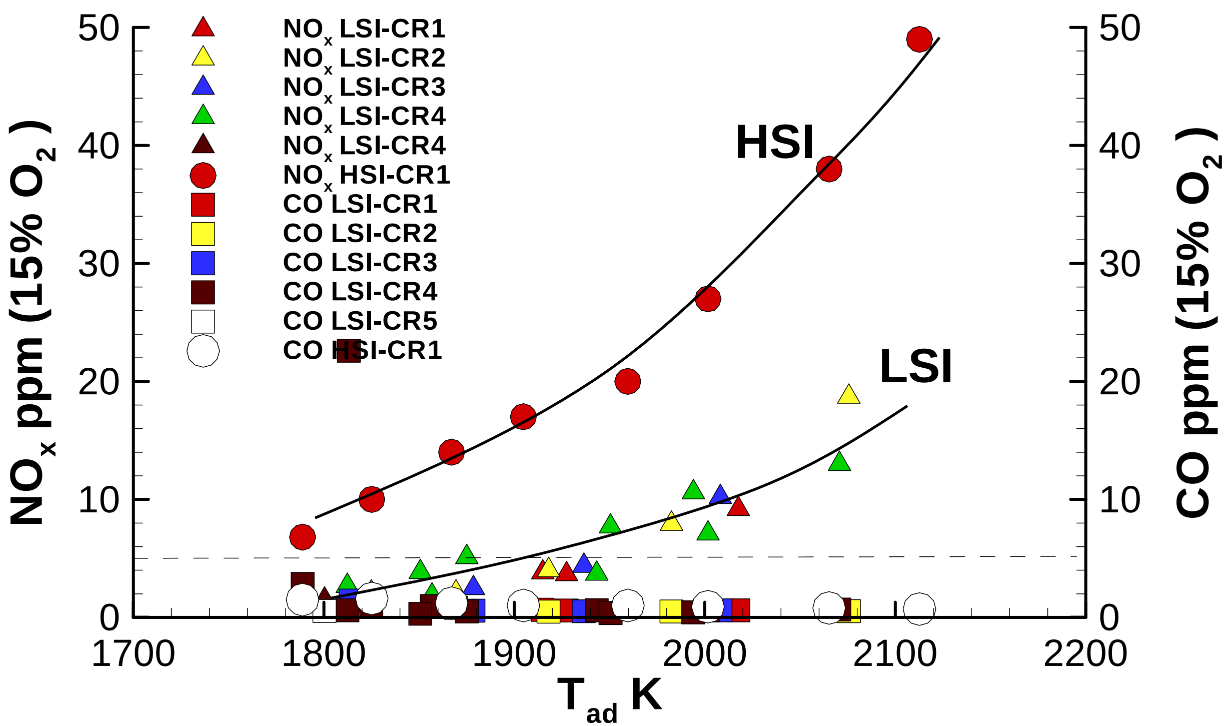
- LSI built from SoLoNOx swirler
  - Replace centerbody with perforated screen
  - Apply guidelines from LSB development





Rig Tests Results of LSI-1

- Demonstrated low-swirl injector concept at full and partial loads (500 < T_{in} < 900F, (5 < P < 14 atm)
- NO_x emissions of LSI 60% lower then conventional DLN high-swirl injectors
- CO emissions well below acceptable limit



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FY04-05 Tasks

1. Pilot integration
2. Premixer development
3. Engine compatible LSI
4. Laboratory studies

Pilot Integration

- Needs
  - Pilot flame is an essential component for light-off, load change, and off-design operating conditions
  - Demonstrate that the LSI can operate within the T70 engine cycle
- Challenges
  - The pilot alters the flowfield produced by the LSI and can have a direct effect on the basic flame stabilization mechanism and emissions
  - No convenient place to mount pilot due to absence of a centerbody in LSI

Developed Embedded Central Pilot

- Embedded central pilot gives the best performance among several different options
  - Particle image velocimetry (PIV) measurements and computational fluid dynamics (CFD) to optimize pilot tube size and assess effects on flowfield

LSI-2 with embedded pilot

Premixer configuration

- Needs
  - Homogeneity of the main fuel/air premixture affects emissions and flame stability
- Opportunity
  - Prior rig-tests showed LSI tolerates some degree of in-homogeneity
  - Such leniency indicates that LSI affords a simple and compact premixer amenable to simple fabrication

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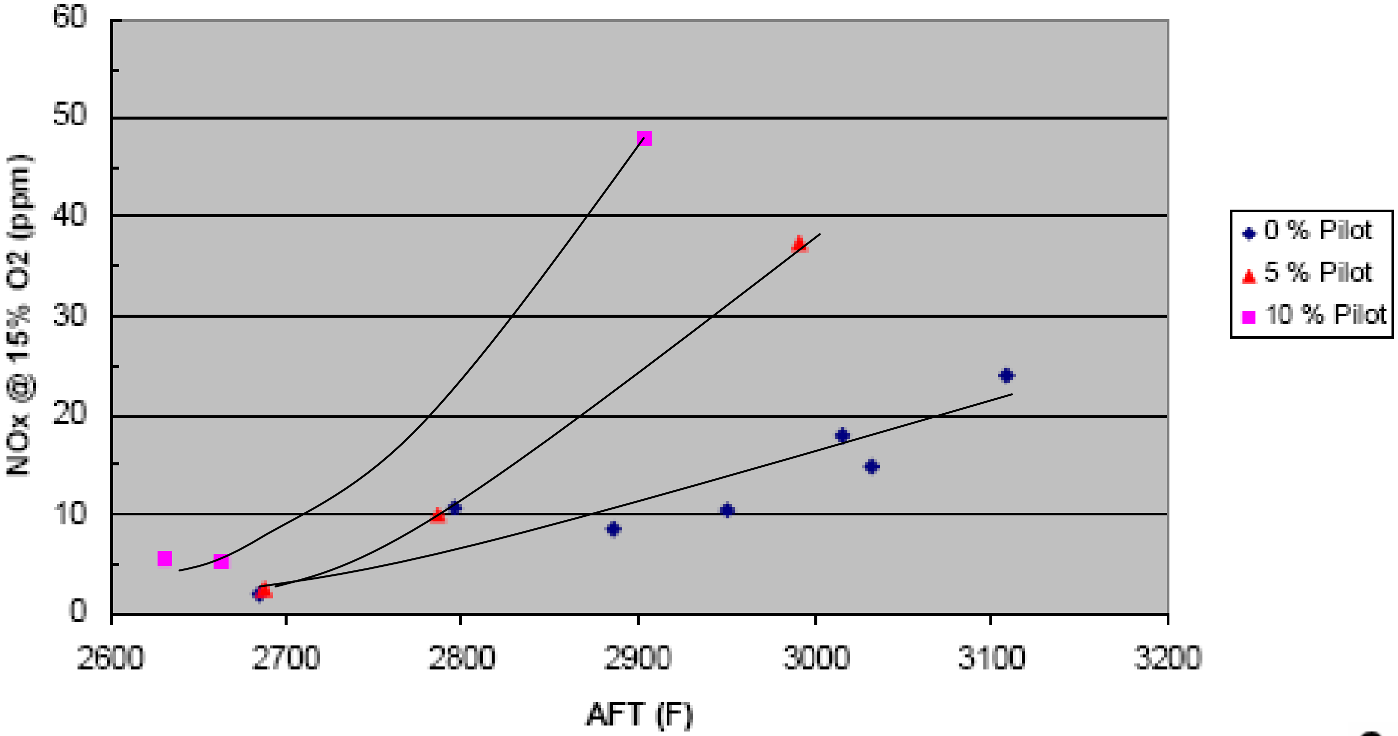
Configured simple multi-tube premixer

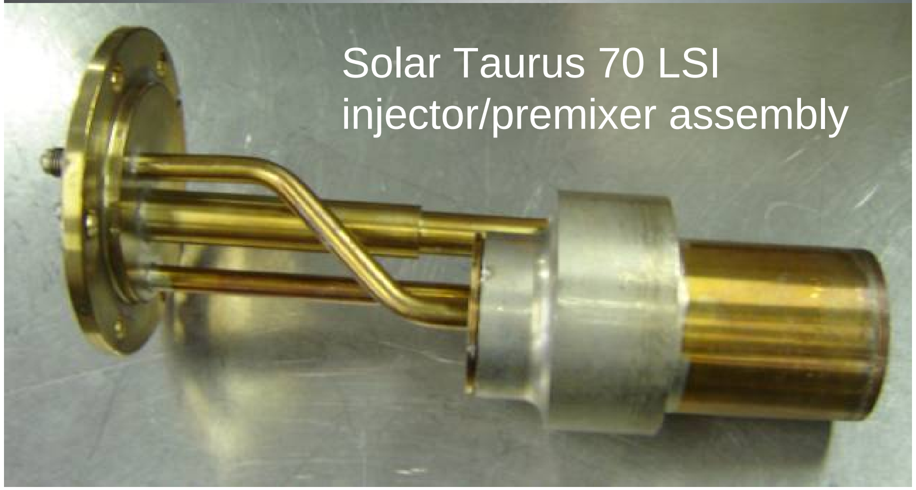
- Leverage on current SoLoNOx premixer design
  - Extend fuel tube to supply center channel
- Optimize to achieve desired homogeneity
  - Varied the number and locations of the injection ports
- Laboratory experiments at atmospheric conditions to verify functionality
  - Comparison of flowfields and flame positions with well mixed cases

Fully functional LSI-2 meets all metrics

- High-pressure tests of LSI-2 with a pilot and premixer showed a wide stable operating window with pilot of 0 to 30%
- LSI-2 can stay lit at AFT of 1900 F with 30 % pilot



Engine compatible LSI-3



- LSI-3 built from SoLoNOx swirler
  - Significant savings in engineering and fabrication
- Same overall size and mounting configuration as T70 SoLoNOx injector
  - Ready for annular liner and engine tests
- Built 15 injectors
  - Selected two at random for baseline performance tests

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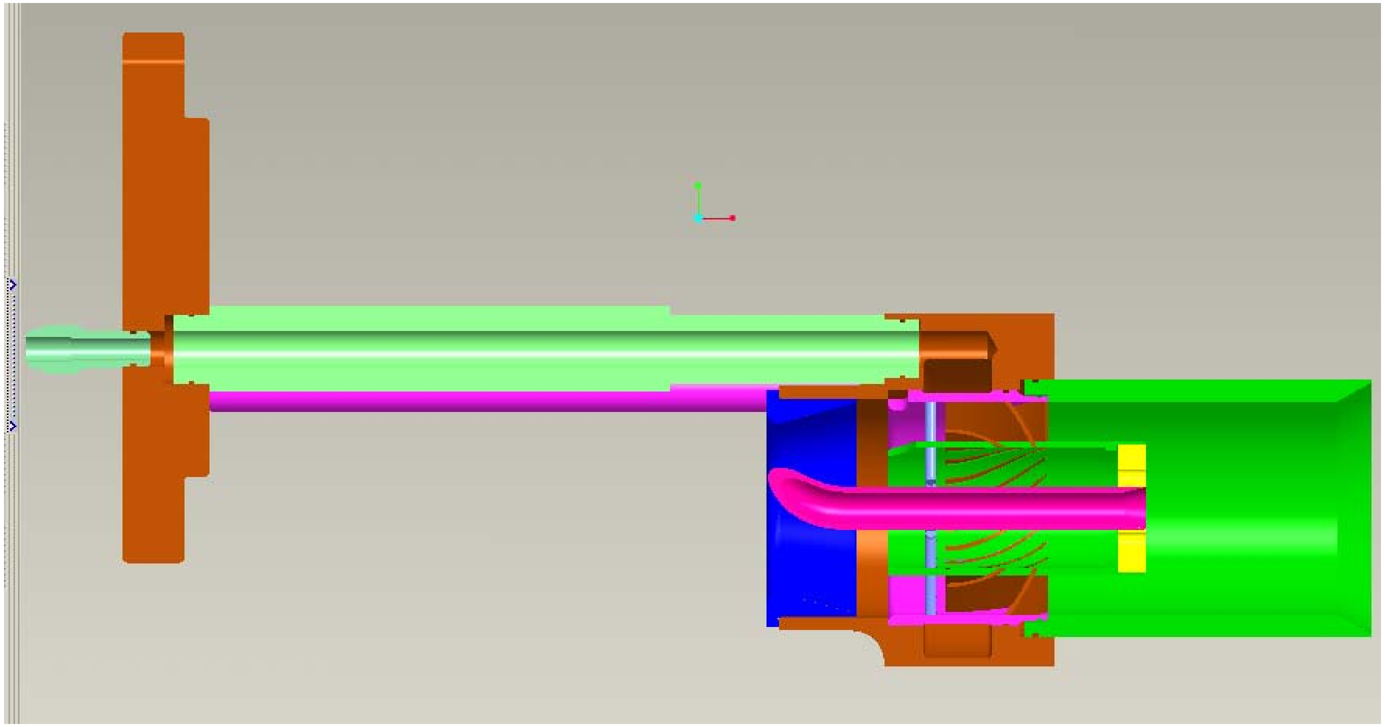
Engine Compatible LSI-3

- Less complex design than SoLoNOx
- Active tip cooling not necessary



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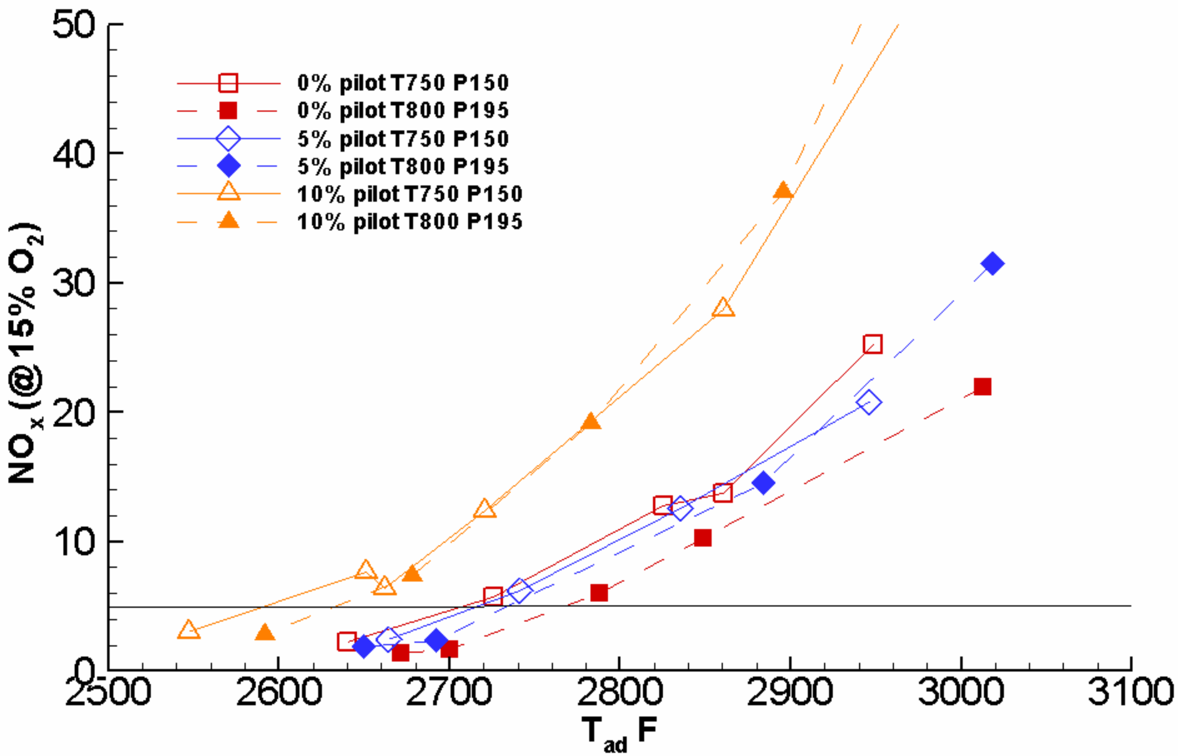
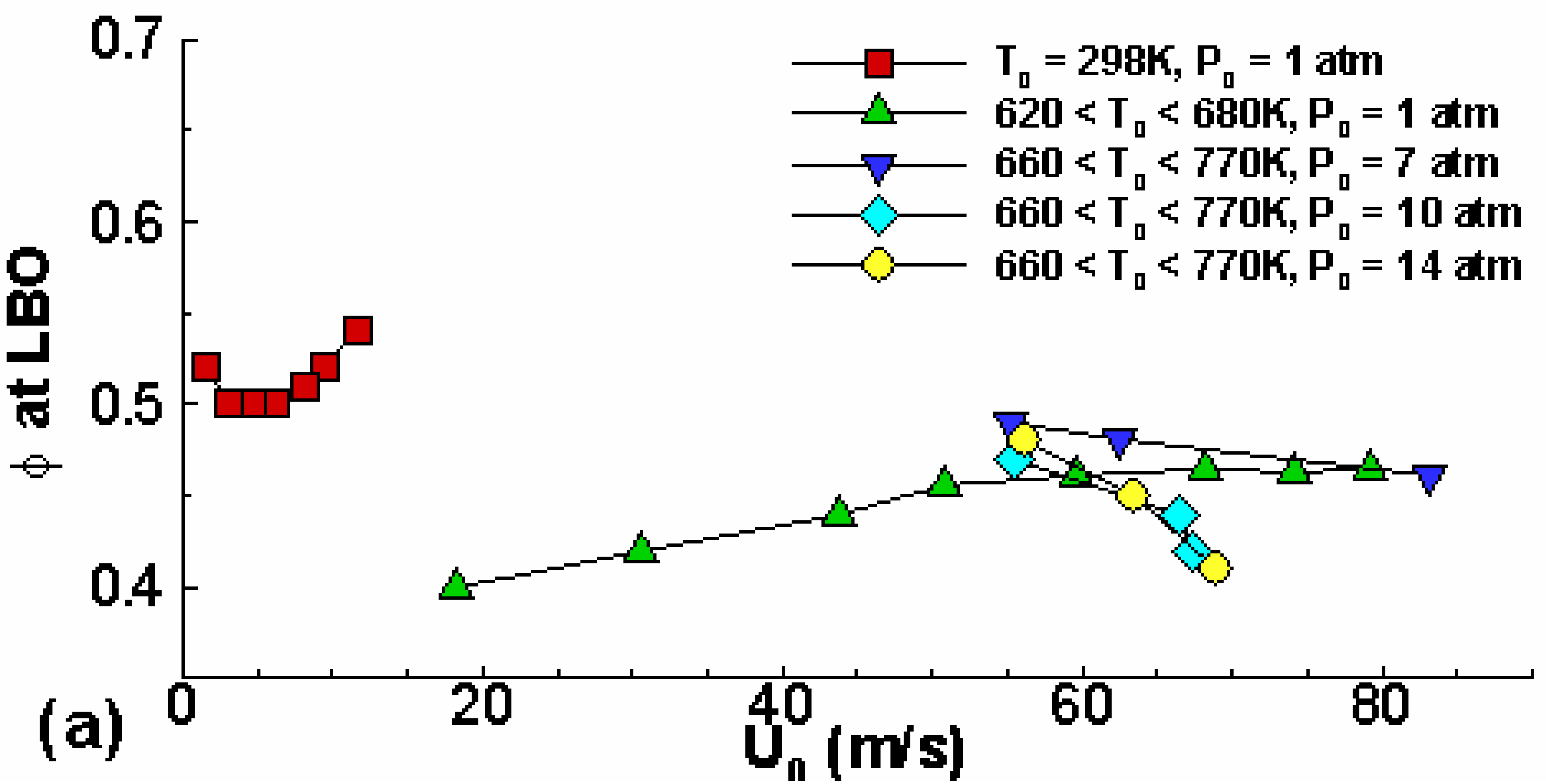
Baseline Performance of LSI-3

- 5% pilot offers ultra-low NO_x and extends LBO
- NO_x < 2.5 ppm at T_{ad} < 2700F & < 5 ppm at T_{ad} < 2750F
- CO well below acceptable levels
- 30% pilot extends LBO to T_{ad} = 2160 F at idling condition
- LSI-3 does not suffer from significant tip heating



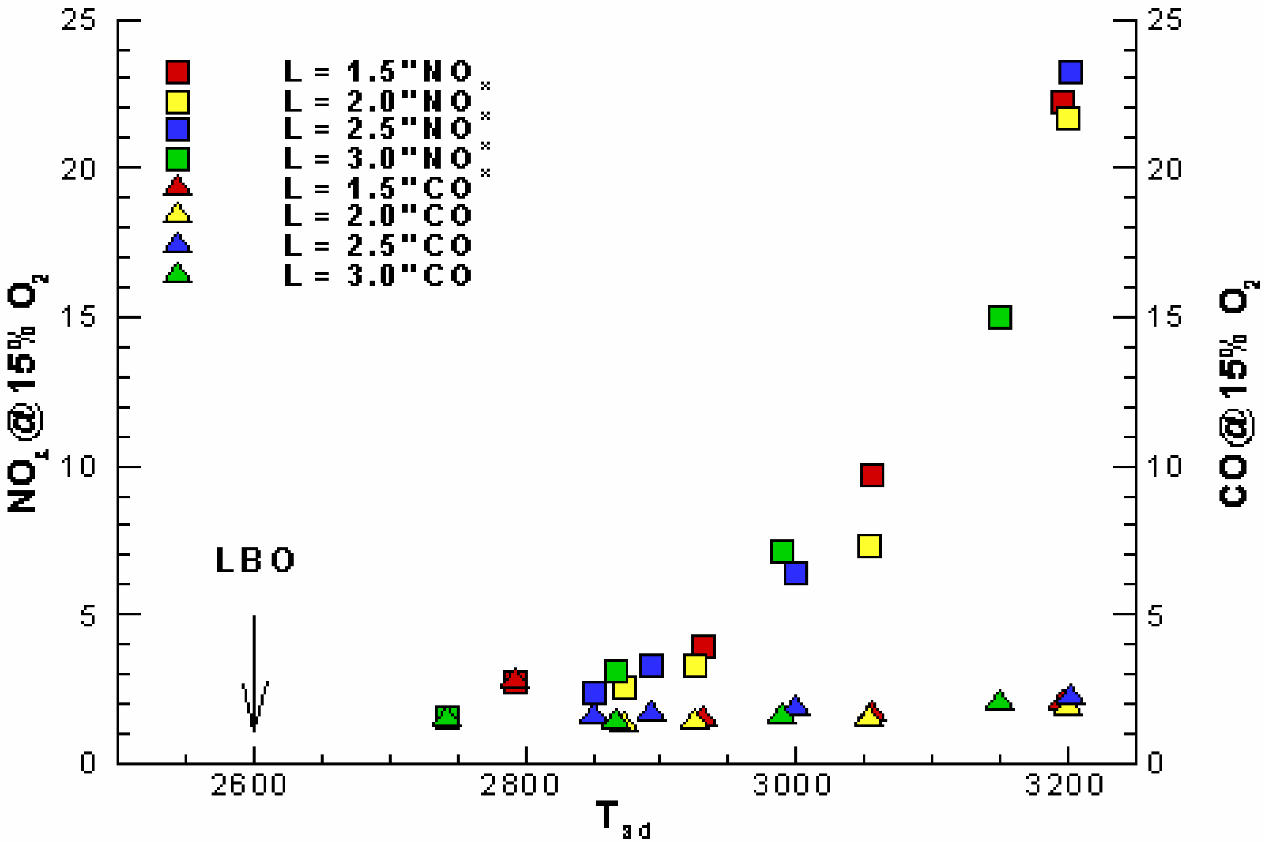
LBO determined at U_0 60% above design point

- LBO remains relatively insensitive to U_0

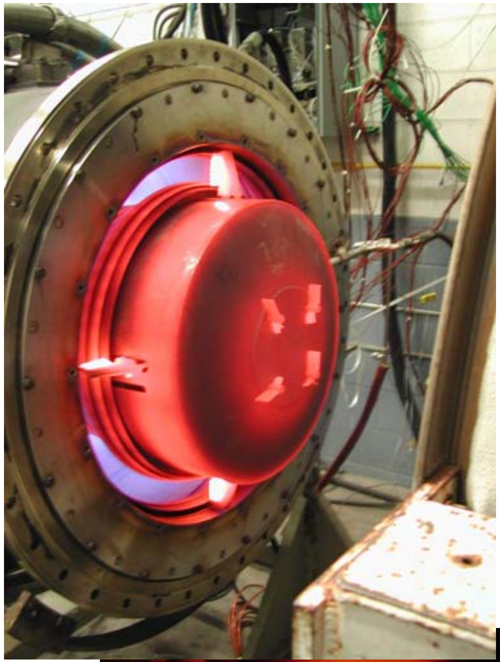


Emissions and LBO Independent of Barrel Length

- Varied barrel length from 1.5 to 3.0”
- Tested at T_0 = 800 F, P_0 = 14 atm & 3 lb/sec



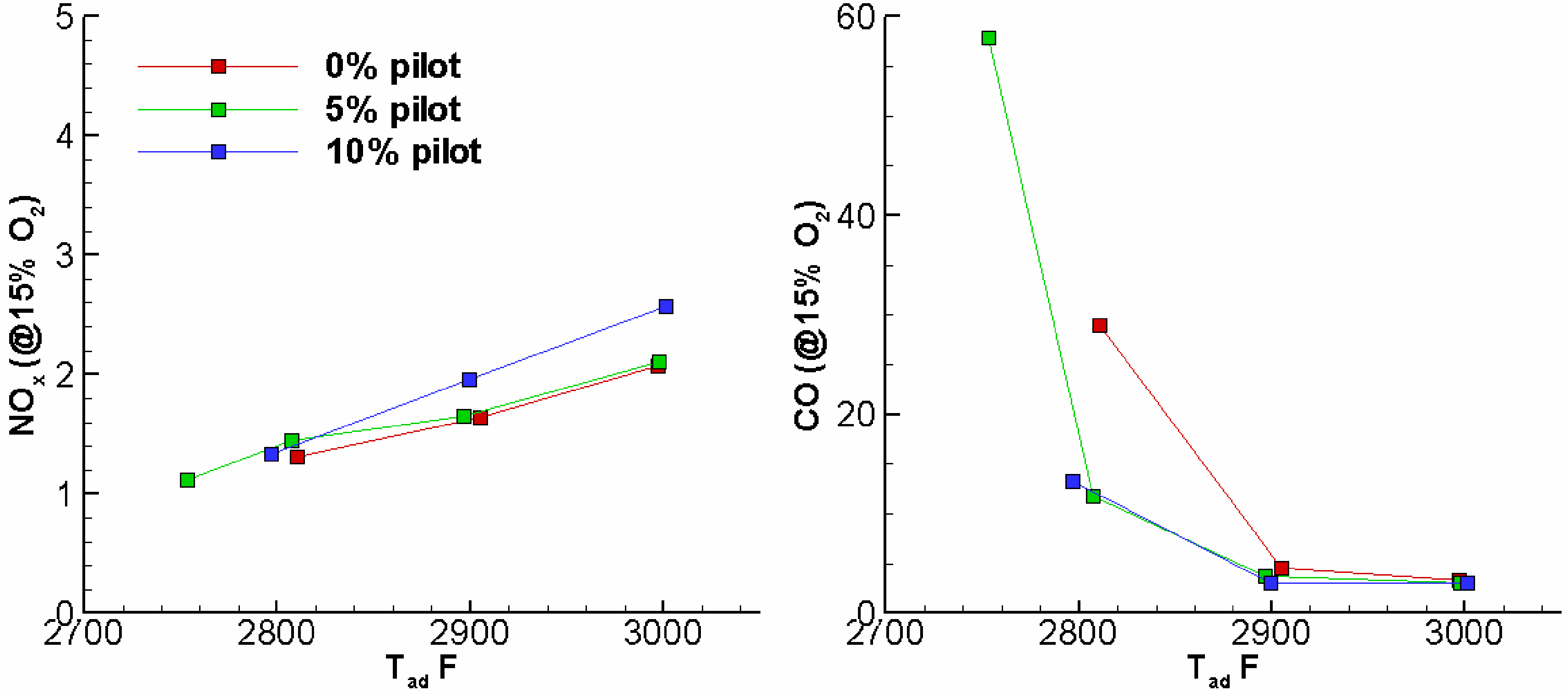
Atmospheric Annular Liner Tests



- 12 LSI-3 fitted to a T70 annular liner and evaluated at simulated partial and full load with 0, 5 and 10% pilot.
- Circumferential and radial temperature distributions were within the acceptable limits
- LSI-3 showed excellent light-around characteristics with no indication of combustion harmonics or injector to injector interactions

LSI-3 Emissions in Annular Liner

- Trends similar to single injector tests
- LSI-3 ready for T70 engine tests



Impact

- Our research has produced a very cost effective ultra-low emissions injector that does not require sophisticated materials or chemicals nor alteration of the overall engine layout or the operation cycle
- Uniqueness in approach
  - Exploit combustion aerodynamics
  - Pursue engineering development guided by scientific background knowledge and supported by parallel laboratory studies

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Meeting DE Program Goals

- ***Cost-effective R&D*** – modest LSI project budget
- ***Lowering costs of DE –*** LSI does not impact first, operating and maintenance costs
- ***Reducing emissions –*** LSI is highly effective in reducing emissions to < 5 ppm NO_x
- ***Improving reliability and performance –*** LSI does not compromise service life and has potential for efficiency enhancement
- ***Expand opportunities for DE equipment –*** LSI provides an enabling technology for fuel-flexible turbines of all sizes

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Future Work

- **Conduct T70 engine tests**
    - In house (Jan. 2006), Field test (TBD)
- **Commence Fuel Flexible LSI Development**
    - **FY06**
        - Laboratory demonstration of fuel-flexible LSIs
        - Designs of fuel-flexible LSIs dedicated to different ranges of Wobbe indices
    - **FY07**
        - Laboratory demonstration of gas-liquid LSI
        - Verify fuel-flexible LSI prototypes at industrial turbine and microturbine conditions
        - Verify natural gas-liquid LSI at engine conditions
    - **FY08**
        - Engineering design guidelines for fuel-flexible LSIs
        - Engine-ready fuel-flexible LSI prototypes for industrial turbines and microturbines
        - Engine ready natural gas-liquid LSI prototype
        - Identify efficiency, performance and DE generation enhancement options

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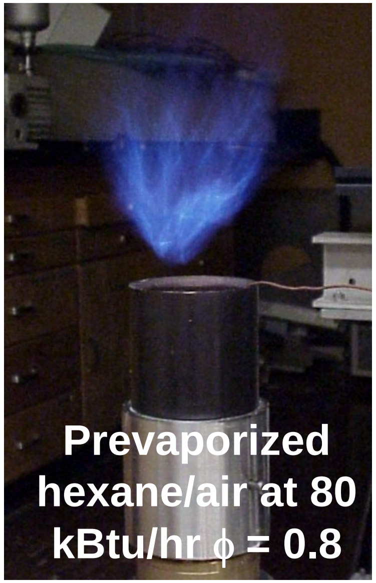
Laboratory Studies Leading to Fuel-Flexible LSI

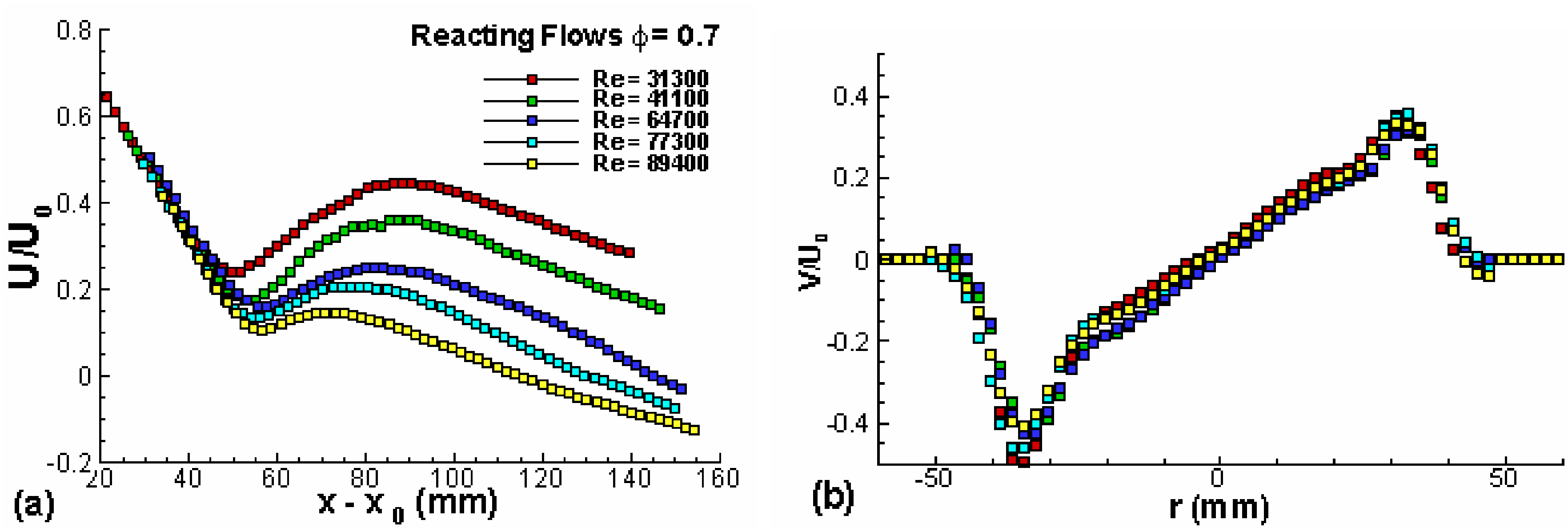
- Lean blow-off measurements for different fuels
- Variations in LSI configurations
  - Changing swirl number
  - Changing barrel tube lengths
- Firing with different fuels
- Further development of an empirical model through flowfield and emissions measurements

Firing with Alternate Fuels



- Liquid fuels
  - Laboratory demonstration of hexane premixed flame at STP
- Low heating value fuels
  - Performed laboratory experiments on a 50/50 CH_4/CO_2 fuel
- Refinery Gases
  - Demonstrated feasibility by firing different blends of natural gas, C_3H_8 and H_2

Investigated Flowfield Development



- Velocity measurements show flowfield similarity
- Defined two parameters to characterize the similarity features of the divergent flow

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Empirical Model for Future Development

- Predicts LSI flame positions based on flame speed correlation and similarity parameters
- Explains why LSI flame positions remains invariant
- Basis for scaling LSI to accept other fuels